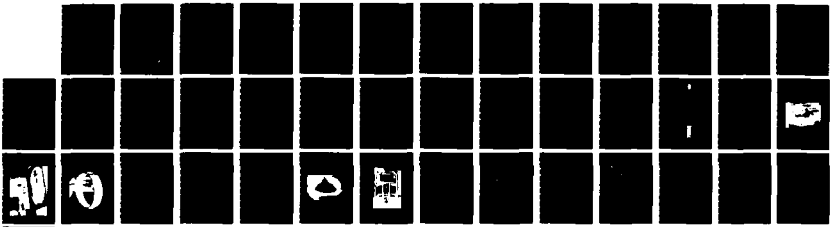
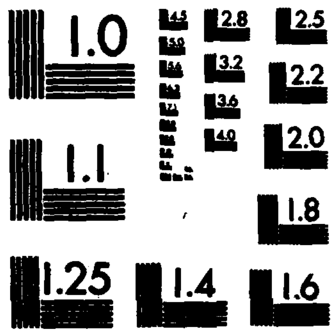
AD-A135 339 DESIGN CONSTRUCTION AND TEST OF A 061-METER-DIAMETER EPOXY IMPREGNATED SU..(U) DAVID W TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER ANN.. 1/1

UNCLASSIFIED D J WALTMAN ET AL. OCT 83 DTNSRDC/PAS-81/18 F/G 21/3 NL



END
FILMED
1-84
DTIC



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

AD-A135339

DTNSRDC/PAS-81/18

(2)

DAVID W. TAYLOR NAVAL SHIP RESEARCH AND DEVELOPMENT CENTER

Bethesda, Maryland 20084

DESIGN, CONSTRUCTION, AND TEST OF A 0.61-METER-DIAMETER, EPOXY IMPREGNATED SUPERCONDUCTIVE MAGNET

by

D. J. Waltman
M. J. Superczynski
and F. E. McDonald

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

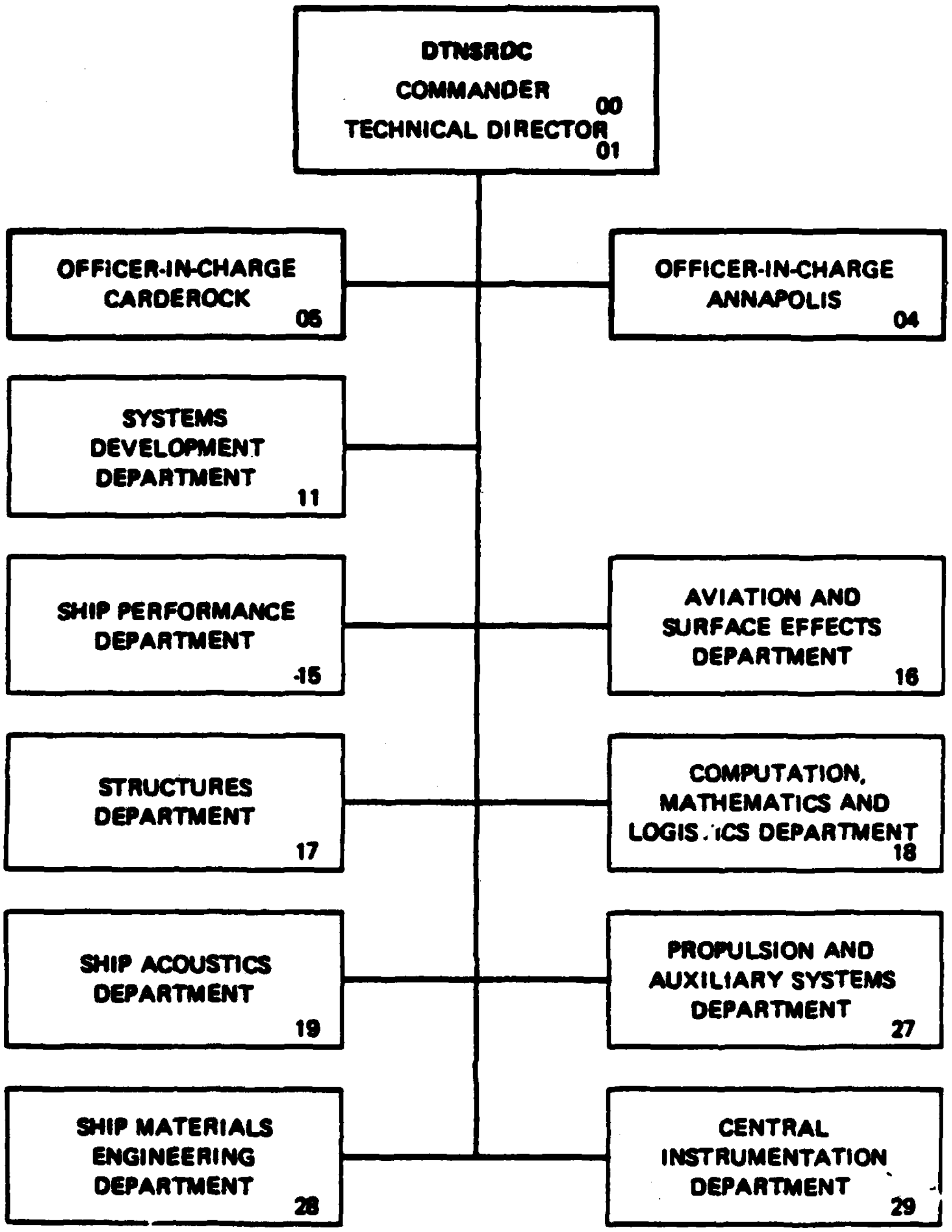
PROPULSION AND AUXILIARY SYSTEMS DEPARTMENT
RESEARCH AND DEVELOPMENT REPORT

October 1983

DTNSRDC/PAS-81/18

DESIGN, CONSTRUCTION AND TEST OF A 0.61-METER-DIAMETER, EPOXY IMPREGNATED SUPERCONDUCTIVE MAGNET

MAJOR DTNSRDC ORGANIZATIONAL COMPONENTS



REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: DTNSRDC/PAS-81/18	2. GOVT ACCESSION NO.: AD-A135339
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle): DESIGN, CONSTRUCTION, AND TEST OF A 0.61-METER-DIAMETER, EPOXY IMPREGNATED SUPERCONDUCTIVE MAGNET	5. TYPE OF REPORT & PERIOD COVERED: Research and Development
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): D. J. Waltman, M. J. Superczynski, and F. E. McDonald	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: David Taylor Naval Ship R&D Center, Annapolis, Maryland 21402	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Task Area SF43431503, Task 23044, Work Unit 2710-100
11. CONTROLLING OFFICE NAME AND ADDRESS: David Taylor Naval Ship R&D Center, Propulsion and Auxiliary Systems Department, Annapolis, Maryland 21402	12. REPORT DATE: October 1983
	13. NUMBER OF PAGES: 38
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Superconductivity
Stability
Magnets
Superconductors

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

To determine the performance and quench behavior of a large, fully-potted, NbTi superconductive magnet, a 0.61-m test coil has been constructed which contains heaters, thermocouples, and strain gauges installed at various winding locations. The magnet has an inductance of 49 henries, 7502 turns of copper stabilized NbTi wire, and a magnet load-line critical point of 190 amperes at 6.5 tesla. The methods and techniques used to construct the fiber glass reinforced, epoxy impregnated magnet are described. The

Block 20

results of the electrical and thermal measurements of the test coil behavior for quenches initiated at various winding locations and at operating currents of up to 150 amperes are presented. The laboratory measurements results are compared to the results obtained from the QUENCH computer program simulation of this magnet to assess the program's ability to describe the actual quench behavior of the magnet.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

Amp	Ampere
C	Temperature, Degrees Celsius
cm	Centimeter
I	Magnet operation current
IC	Superconductor critical current
I.D.	Inside diameter
K	Temperature, Kelvin
kV	Kilovolt
m	Meter
max	Maximum
min	Minimum
mm	Millimeter
MW	Megawatt
N	Newton
NbTi	Niobium titanium alloy
Nb48Ti	NbTi, 48 percent by weight titanium
n/m^2	Newtons per square meter
O.D.	Outside diameter
psi	Pounds per square inch
sec	Second
VDC	Volt direct current

ABSTRACT

To determine the performance and quench behavior of a large, fully-potted, NbTi superconductive magnet, a 0.61-m test coil has been constructed which contains heaters, thermocouples, and strain gauges installed at various winding locations. The magnet has an inductance of 49 henries, 7502 turns of copper stabilized NbTi wire, and a magnet load-line critical point of 190 amperes at 6.5 tesla. The methods and techniques used to construct the fiber glass reinforced, epoxy impregnated magnet are described. The results of the electrical and thermal measurements of the test coil behavior for quenches initiated at various winding locations and at operating currents of up to 150 amperes are presented. The laboratory measurements results are compared to the results obtained from the QUENCH computer program simulation of this magnet to assess the program's ability to describe the actual quench behavior of the magnet.

ADMINISTRATIVE INFORMATION

The work described in this report was performed as part of the Advanced Electric Drive Program, Task Area SF43431503, Task 23044, sponsored by the Naval Sea Systems Command (SEA 05R31). The work was performed under Work Unit Number 2710-100 in the Electrical Machinery Technology Branch of the Electrical Systems Division, Propulsion and Auxiliary Systems Department of the Center.

INTRODUCTION

The Navy is currently developing the technology required to design and build advanced d.c.* motors and generators for ultimate application in ship electric propulsion systems. One of the objectives of this program is to develop a compact and efficient superconductive electric drive system for surface ship applications of up to 58 MW of power per propeller shaft. The electric motors and generators in the superconductive ship drive system would be acyclic, d.c. machines that will use superconductive solenoidal field

*Definitions of abbreviations used are given on page v.

magnets to produce the high density magnetic fields required. These field magnets will be wound with copper stabilized, NbTi superconducting wire, will be fully potted, and reinforced with fiber glass cloth. Besides having the advantage of high overall current density, this magnet construction technique also provides a mechanically rigid magnet composite to prevent relative conductor motion that could produce frictional heating and a threat to magnet stability. However, fully-potted magnets do have several inherent weaknesses that can limit their performance and reliability. Large stress concentrations can develop within the windings during magnet construction and its subsequent cool-down to 4.2K. These stresses represent stored energy which can be released when the magnet is energized. If the local strain developed by the magnetic hoop force exceeds the failure limit of the epoxy, the epoxy will crack and a local temperature rise will develop, resulting in a possible quench of the magnet. Therefore, the magnet must be wound with a composite superconductor having a sufficient amount of copper matrix material to safely dissipate the energy stored in the magnetic field of the coil during a quench. The safe dissipation of the stored energy of the magnetic field includes limiting both the maximum hot spot temperature of the winding and the internal voltages developed to values compatible with the magnets' materials of construction.

To determine the performance and quench behavior of a large, fully-potted, NbTi superconducting magnet, a 0.61-m test coil has been constructed. This test coil is instrumented with heaters, thermocouples, and strain gauges installed at various locations in its winding. With this coil a quench can be purposely initiated at various winding locations, and the electrical and thermal behavior of the magnet can be measured during the quench period. This report describes the design and construction of the 0.61-m test coil and the measurements of its performance during a quench. The measured quench results are compared to the analytical results obtained from a computer analysis using the QUENCH computer program to determine the program's ability to correctly predict the quench behavior of a large, potted superconducting magnet.

TEST COIL DESCRIPTION

The 0.61-m test coil is a fully-potted, vacuum-impregnated, fiber glass-reinforced solenoid. The overall dimensions of the test coil are shown in

Figure 1. The physical dimensions of the finished coil are 61.21-cm I.D., 68.43-cm O.D., and 15.24-cm length. The coil contains 46 layers of winding and has a total of 7,502 electrical turns of copper stabilized NbTi superconducting wire and a total inductance of 49 henries. The superconducting wire contains 168 filaments of Nb48Ti superconductor having a twist pitch of 1.69 cm and has a copper-to-superconductor cross-sectional area ratio of 2 to 1. The wire is rectangular in cross section, has overall dimensions of 0.660 by 0.914 mm, and is coated with Formar insulation approximately 13-microns thick.

TEST COIL CONSTRUCTION

COIL WINDING SYSTEM

The test coil was wound on a specially constructed aluminum coil form shown in Figure 2. This coil form, with the addition of an outer cylindrical shell, also served as the potting chamber for impregnating the completed coil with epoxy resin. A modified machine lathe equipped with a variable speed reversible motor was used to turn the coil form to wind the test coil. Wire winding tension was developed by applying reverse torque to the wire supply reel through a controllable hysteresis clutch mechanically attached to the supply reel. The clutch was driven by a fractional horsepower motor in a direction opposite to the supply reel rotation. The wire was cleaned during the coil winding process by drawing it through a cleansing assembly consisting of a liquid Freon jet stream and several felt wiping pads. A simplified drawing of the superconducting coil winding system used to construct the 0.61-m test coil is shown in Figure 3.

COIL CONSTRUCTION PROCEDURE

Prior to winding the first layer of wire, three layers of 0.089-mm-thick, type S, fiber glass cloth were wound onto the coil form mandrel. Each layer of fiber glass was made with an individual strip of cloth of sufficient length to completely cover the circumference of the mandrel with approximately a 0.635-cm overlap at the ends. The widths of the cloth layers were selected to allow coverage of the sides and outer circumference of the completed winding with a 0.635-cm overlap at the center line of the outer coil surface. This complete coverage of the entire surface of the wound coil is necessary to provide continuous reinforcement of the magnet. After the initial layers of

fiber glass cloth were wound on the mandrel, a layer of superconducting wire was wound over the fiber glass base. The input electrical lead and the first electrical turn of the coil are of soldered double-wire construction. Similarly, the last electrical turn and exit lead of the completed winding are also soldered double leads. This was done to ensure the electrical-mechanical integrity and performance of the current leads of the magnet which are subjected to mechanical abuse during magnet construction and operation. After the first layer of winding was completed, a layer of 0.089-mm-thick fiber glass cloth was wound onto the winding layer. Then, the next layer of wire was wound over the layer of cloth. This winding procedure was continued with alternate layers of wire and cloth for a total of 46 layers and 7,502 turns. The outer surface of the wound coil was then wrapped with multiple layers of 0.089-mm-thick fiber glass cloth to provide an external hoop force restraint member and protection for the outer layer of superconducting wire.

The wire used to wind the test coil was not manufactured in a single length that was sufficient to complete the winding of the coil. The coil winding therefore required a splice at the first turn of layer 42. The wire used to complete the winding was identical to and manufactured from the same billet as the wire of the previous turns. The winding was spliced over one complete turn of the coil with the two wires soldered together on their sides. Using a one-turn splice allowed the ends of the two superconducting wires to butt with a minimum void in the coil. Each exposed end at the butt of the two-wire splice was electrically insulated with varnish to eliminate the possibility of a shorted turn.

COIL INSTRUMENTATION

During the winding of the test coil, wire heaters, thermocouples, and strain gauges were located at various positions about its inner bore and outer surface, as shown in Figure 4 and described in Table 1. The heaters, thermocouples, and strain gauges located on the inner bore of the magnet were installed directly in physical contact with the first layer of superconducting wire. The heaters, thermocouples, and strain gauges located on the outer surface of the magnet were placed on the first layer of fiber glass cloth that covers the last layer of wire. Therefore, one thickness of cloth physically separates the heaters and sensors from the final layer of magnet winding.

TABLE 1 - TEST COIL INSTRUMENTATION

Instrumentation Set Number	Clock Location*	Instrumentation Description**	Instrumentation Axial Distance (cm) From Top Of Coil*** +
		Inner Bore	
H1	3:30	1 Heater 1 Type T and 1 Type K Thermocouple	H:5.56, T:5.87, K:4.92
H2	12.00	1 Heater 1 Type T and 1 Type K Thermocouple	H:6.83, T:7.14, K:6.51
H3	8:15	1 Heater 1 Type T and 1 Type K Thermocouple	H:7.30, T:7.46, K:6.98
S4	2:00	1 Strain Gage	6.83
S5	10:30	1 Strain Gage	6.98
S6	5:15	1 Strain Gage	6.98
		Outer Surface	
H7	12:00	1 Heater 1 Type T and 1 Type K Thermocouple	H:7.78, T:8.09, K:7.46
H8	3:30	1 Heater 1 Type T and 1 Type K Thermocouple	H:7.78, T:8.09, K:7.46
H9	8:30	1 Heater 1 Type T and 1 Type K Thermocouple	H:7.62, T:7.93, K:7.30
S10	2:00	1 Strain Gage	7.62
S11	6:00	1 Strain Gage	7.62
S12	11:00	1 Strain Gage	7:30

*See Figure 4.
**Type J-copper/constantan thermocouple; type K-gold chromel thermocouple.
***H = heater location in cm; J = type thermocouple location in cm; K = type K thermocouple location in cm.
+Top of coil is defined as the coil end at which the current leads enter and exit the coil.

At each of the instrumentation set location numbers designated H1 through H9, one heater consisting of bare chromel wire 25.4-mm long and 0.127-mm diameter was installed in the coil with the heater axis oriented parallel to the wire of the coil. The current leads for the heaters were made with small diameter, insulated, copper wires that were twisted together and run, perpendicular to the winding, up along the surfaces of the inner bore (H1, H2, H3) and the outer circumference (H7, H8, H9), exiting the magnet structure on the same coil end as the current leads of the magnet. For reference purposes, the current lead end of the magnet was designated the top of the coil, as shown in Figure 4. At each instrumentation location containing a heater, one copper-constantan (type T) thermocouple, and one gold-chromel (type K) thermocouple were installed in close proximity with the heater. The physical locations of the thermocouples are given in Table 1. The thermal reference junctions for both the copper-constantan and gold-chromel thermocouples were established at the 4.2K liquid helium bath temperature.

In addition to the temperature measuring sensor, strain gauge sensors were located on the inner bore and outer circumference of the coil at locations S4, S5, S6, and S10, S11, S12, as shown in Figure 4. The physical locations of the strain gauges are given in Table 1. The strain gauges used are two section, orthogonal reading, 120 ohm, constantan wire strain gauges. One sensing section of each strain gauge was oriented along the parallel to the wire of the coil, and the other orthogonal sensing section was therefore oriented perpendicular to the wire and in parallel with the axis of the coil.

TEST COIL POTTING PROCEDURE

After completion of the winding of the superconducting test coil, a metal cylindrical shell was placed around the coil and clamped in place (see Figure 2 and 5). The combination of the coil form, cylindrical shell, and O-ring seals, as shown in Figure 2, served as the potting chamber for vacuum impregnating the coil winding with epoxy resin. The assembly of the coil and potting chamber was wrapped with electrical heater tape and placed in a thermally insulated box, as shown in Figure 6, to maintain the coil at a temperature of 65°C during its potting process.

The impregnant used to pot the test coil is composed of Ciba 6004* epoxy resin and Lindride 12* and Lindride 16* hardner mixed in equal parts. The proportions of resin and hardener are 100 parts to 85 parts by weight, respectively. Before mixing, the epoxy components were first heated to 65°C and vacuum degassed to a pressure of approximately 40 microns. The components were then mixed together in ambient atmosphere at a temperature of 65°C for approximately 10 minutes. This mixture was degassed to a pressure of 40 microns and then piped into the coil potting chamber which had been evacuated to a pressure of approximately 10 microns. After the completion of the epoxy transfer, the pressure of the potting chamber was increased to 6.89×10^5 N/m^2 (100 psi) using nitrogen cover gas to force the impregnant into the windings of the coil. This pressure and a potting chamber temperature of 65°C were maintained for a period of 20 hours to cure the epoxy. To ensure that the epoxy had cured, the pressure of the potting chamber was reduced to atmospheric pressure, and its temperature was raised to 80°C, where it was maintained for an additional 24 hours. The potting chamber was allowed to cool to room temperature, and the coil was removed from the chamber. All excess epoxy was removed from the coil, and it was then machined to its final dimensions. A photograph of the test coil taken upon completion of construction and removed from its coil form is shown in Figure 7.

To provide additional mechanical restraint to the composite of the coil, which must withstand the action of the large magnetic forces produced in the magnets winding, a cylindrical retaining ring (Figure 8) was fitted over the outer surface of the test coil. A circular disk fabricated from 0.635-cm-thick 6061 aluminum alloy, (Figure 9) was attached to the bottom end of the outside cylindrical retaining ring. Another circular disk (Figure 10) fabricated from 0.635-cm-thick, laminated, fiber glass sheet was attached to the top end of the cylindrical retaining ring. This disk provided a mounting platform for the instrumentation terminal boards used for connecting the electrical leads of the coil heaters and sensors to the control and data acquisition cables of the laboratory test equipment. A photograph of the

*Ciba 6004 is manufactured by Ciba Products, Co., N.J.; Lindride 12 and 16 hardeners is manufactured by Lindan Chemical, Inc., Columbia, S.C. Trade names are used to define the material and do not imply any endorsement of products by DTNSRDC.

completed test coil assembled with its restraint members is shown in Figure 11.

CURRENT LEADS

Each of the current leads of the test coil winding (soldered double superconducting wires) were soldered in parallel with a 1.59-cm-wide length of copper braid. This parallel combination, 0.91-m in length for each lead, starts at the point where the winding leads physically exit the magnet composite and terminates above the coil at a pair of vapor cooled leads. The purpose of the braided material is to improve current transfer from the ventilated copper rod, vapor-coiled current leads to the superconducting magnet wire.

LABORATORY MEASUREMENTS

The completed test coil, assembled in its suspension-type mount with its instrumentation cables and current leads connected and ready for installation in a open mouth dewar, is shown in Figure 12. Also shown is a heat shield for the upper portion of the dewar bore made from stacked alternate layers of plastic foam, cryogenic insulation, and sheets of super insulation.

For the experiments the test coil assembly is installed in its dewar, and a superconducting magnet power supply having a maximum output current capacity of 180 amperes is used to energize the test coil. The magnet load-line for the 0.61-m test coil and its conductor short sample characterisitics are shown in Figure 13. As can be seen the magnet critical point at 4.2K along its load line is 6.5 tesla and 190 amperes.

The data acquisition system for the experiments consists of a multiple-channel, strip chart recorder used to measure and record the magnet operating current and the winding temperatures of the magnet. A pulse generator and current amplifier were used to deliver a current pulse of known energy to the heater selected to initiate a quench of the magnet.

Prior to performing the experiments a check-out of the instrumentation installed in the coil revealed that the instrumentation at several locations had been damaged during the assembly of the coil. At instrumentation location H1 the heater and both thermocouples were open circuited. At locations H2 and H3 the heaters were short-circuited to the copper/constantan thermocouples, and at locations H7 and H8 the copper/constantan thermocouples showed an open circuit. The heater at H2, in addition to showing a short to the copper

constantan thermocouple, also measured a lower than normal resistance, indicating that a section of its length was shorted through the thermocouple. The heater at H3, although having a short to the H3 copper construction thermocouple, measured the proper resistance and was considered operational. However, even with these numerous failures, the location redundancy of the instrumentation design provided sufficient, usable instrumentation at the magnet's inner bore and outer circumference to measure the thermal behavior of the test coil during a quench.

Listed in Table 2 are the test runs performed to measure the performance and quench behavior of the 0.61-m test coil. Preliminary tests, though not listed in the table, at magnet operating currents of 30 and 75 amperes were performed to verify magnet and data acquisition system operation.

After being quenched for run 1, the magnet suffered damage to its winding and would undergo a self quench when energized to a current of 30 amperes as indicated in Table 2. Subsequent troubleshooting of the magnet revealed that the coil contained several resistive winding shorts at various locations in the first two winding layers (inner bore region) of the magnet. The subsequent examination and repair of the magnet indicated that the shorts were the result of electrical arcing caused by damage to the magnet wire insulation, which apparently occurred during magnet construction. In addition to repairing the magnet winding, the heater at location H1 was replaced by a 0.127-mm-diameter constantan wire heater 1.9 cm in length. Also, the copper/constantan thermocouples at locations H1 and H2 were replaced with new thermocouples of the same type.

After completion of these repairs, test runs 2, 3, and 4 were performed; after run 4, the test coil again developed a winding short. The winding short was located in the first layer of winding at the location of heater H1. Apparently, this electrical short occurred as a result of accidently burning out heater H1. A failure of the power transistor in the pulse amplifier connected to heater H1 allowed a high value of current to flow through the heater wire, causing it to overheat and burn out. This, in turn, burned the insulation of the magnet wire, and an electrical short developed between two adjacent turns at the heater location. The magnet was repaired by electrically removing the shorted turn from the winding. It was also observed that the replacement copper/constantan thermocouples installed at locations H1

TABLE 2 - 0.6-METER SUPERCONDUCTIVE MAGNET
SUMMARY OF TESTS

Run No.	Coil Current (Amps)	(*) I/Ic	Stored ** Energy (J)	Heater Location No.	Energy To Quench (J)	Max Temp Rise (K)	Time *** Constant (sec)	Max. Coil + Voltage (kV)	Comments
1	100	0.3	245,000	H2			1.5	2.7	Heater to thermocouple short Magnet suffered damage
2	100	0.3	245,000	H1	2.5×10^{-3}	45	1.5	2.7	New H1 Heater: 1.9 cm constantan Poor thermocouple/test coil contact
3	120	0.4	353,000	H1	1.2×10^{-3}	54	1.3	3.9	Poor thermocouple contact
4	129	0.45	408,000	H1	1.1×10^{-3}	62	1.14	5.2	Heater failure Magnet damaged Poor thermocouple contact
5	135	0.5	447,000	H3	6.1×10^{-4}	88	1.04	5.4	Improved thermocouple contact H3: 2.54 cm Chromel
6	150	0.6	551,000	H3	4.0×10^{-4}	99	0.92	6.6	Operating current of 150A is 80% of max magnet load line current

* Ratio of operating current to short sample current.
** $E = 1/2\ LI^2$; L = 49h.
*** Time for coil current to decay to 36.79% of initial current.
\+ V = L dI/dt.

and H2 during the first magnet repair had pulled away from the surface of the inner bore; thus, they were in poor thermal contact with the magnet winding. This condition was corrected and the magnet was then successfully operated and purposely quenched using heater H3 for test runs 5 and 6 at operating currents of 135 and 150 amperes, respectively. The test evaluation was completed with test run 6. At this point, the magnet operating current of 150 amperes represents a value along the magnet load line that is 80% of critical current and field, which is the normal operating design point for a potted superconducting magnet.

A plot of the measured coil currents for magnet quenches for runs 1 through 6 is shown in Figure 14.

LABORATORY MEASUREMENT RESULTS

The results of the experiments to measure the quench behavior of the 0.61-m test coil, (Table 2) show that as the magnet is quenched at successively higher operating currents (thus higher values of stored energy), the measured time constant (time for the operating current to drop to a 36.79% of its initial value) decreases. This clearly is an expected result since almost all of the stored energy in the magnetic field is dissipated in the copper matrix material of the normal regions of the magnet's superconducting wire.* Therefore, as the level of the stored energy increases, the temperature of the hot spot should increase, more wire should be driven normal, and the resistance developed in the winding will increase, resulting in a shorter current decay time constant. The increase in measured coil winding temperature for increasing levels of magnet stored energy is shown in Table 2. The temperature rises presented are maximum temperatures measured for each run regardless of whether they corresponded to the location of the heater. In the cases of runs 2, 3, and 4, the thermocouples were not in good thermal contact with the winding and the temperature measurements reflect this condition, when compared to runs 5 and 6 where the thermal contact was good. The measurements do show an increase in winding temperature for magnet quenches initiated at higher operating currents. For the quench at an

*During a quench, the superconducting magnet power supply limits the coil terminal voltage to approximately 7 vdc. The amount of energy absorbed by the power supply and the resistive cables and connections to the magnet is less than 1% of the total energy stored in the magnet field for all values of operating current.

operating current of 150 amperes, the maximum temperature rise of the coil was 99K. A 100K value is the traditionally accepted design temperature limit for potted superconducting magnets.

COMPUTER PROGRAM RESULTS

The QUENCH computer program, developed by the Rutherford Laboratory in England and modified by Robert Lari of the Argonne National Laboratory, was used to analytically determine the quench behavior of the 0.61-m test coil. The results of the computer simulation were then compared to the measured laboratory results to determine the ability of the computer simulation (and the information provided to it) to accurately compute the quench behavior and characteristics of the test coil.

Presented in Table 3 is a summary of the computer program results for the 0.61-m test coil. Figure 15 is a plot of the magnet current for the computer

TABLE 3 - SUMMARY OF 0.61-METER SUPERCONDUCTIVE MAGNET QUENCH COMPUTER PROGRAM RESULTS

Coil Current (Amp)	Stored Energy (J)	Max. Temperature Rise (k)	Time Constant (Sec)	Max. Coil Voltage (V)
100	245,000	75.6	1.4	3,051
120	353,000	85.2	1.15	4,828
130	414,000	89.5	1.0	5,948
150	551,000	100.0	0.82	8,556

simulated quenches at the operating currents shown. These analytical results were obtained for a quench initiated at the inner bore of the coil at each of the operating currents of Table 2 and Figure 15. Comparison of the computer quench results of Table 3 to the measured results of Table 2 shows that the time constant of the current decay is less for the computed results for each of the operating currents. Therefore, for each of the coil operating currents, the value of the peak internal voltage developed within the windings is greater for the simulated results than for the measured results. A plot of the magnet currents during a quench for both the measured and QUENCH computer program results are shown in Figures 16 and 17 at operating currents of 100

and 150 amperes, respectively. As can be seen the time for the current to decay from its initial value to a 36.78 % value is 0.12 seconds less for the QUENCH computer program results than the measured results for a quench at 100 amperes. At 150 amperes the time constant for the QUENCH simulation current decay is 0.16 seconds less than that for the measured coil current decay. Therefore, in terms of developed internal winding voltage, the results of the QUENCH computer program can be considered a worse case condition. One reason for the difference in the results produced by the computer simulation and those actually measured is that for this initial effort to apply the QUENCH computer program, the mutual inductances of the aluminum reinforcing ring, the lower retaining ring, and the winding of the test coil assembly were not included in the computer simulation. It is planned to include these mutual inductances in the computer simulation program to determine their effect upon the current decay of the test coil during a quench.

Tables 2 and 3 show the measured temperature rise of the test coil during a quench for runs 5 and 6, where good thermocouple contact with the coil existed, is in close agreement with the temperature rise predicted by the QUENCH computer program. This agreement between the measured and predicted temperature rise indicates that for this coil design, the hot spot temperature developed during a quench is within the traditional design safety limit of 100K for potted magnets.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained from the measured quench behavior of the 0.61-m test coil and results predicted by the QUENCH computer program indicate that a high current density, fully-potted superconducting magnet can be designed to safely dissipate the energy stored in its magnetic field without the need for external protection devices. For the 0.61-m test coil design, the dielectric strength of the composite is of more concern than the hot spot temperature developed during a quench. The construction techniques and materials used to fabricate the 0.61-m test coil provide for a measured layer-to-layer voltage breakdown level of 12 kV. Extrapolating the internal voltage valves of both the measured quench results and the computer simulation results indicates that the internal voltage amplitude approaches a level 10 to 12 kV for a quench at the loadline short sample of 190 amperes and 6.5 tesla. This may or may not be a problem, depending upon whether this voltage potential exists between two

adjacent layers, or is distributed across several layers of the winding. Further work is needed to determine the voltage gradients and distribution in the 0.61-m test coil during a quench.

During the testing of the 0.61-m test coil, no evidence of magnet training was observed. Although the magnet suffered several self quenches, each of these could be attributed to insulation or instrumentation problems which apparently developed during magnet construction.

The emphasis of the continuing work in the quench behavior of large potted superconducting magnets will be the development and refinement of the QUENCH computer program. The improvement of the ability of this simulation to predict the quench behavior of the 0.61-m test coil will result in its application to design the full-scale superconductive magnet systems for the ship electric drive motors and generators.

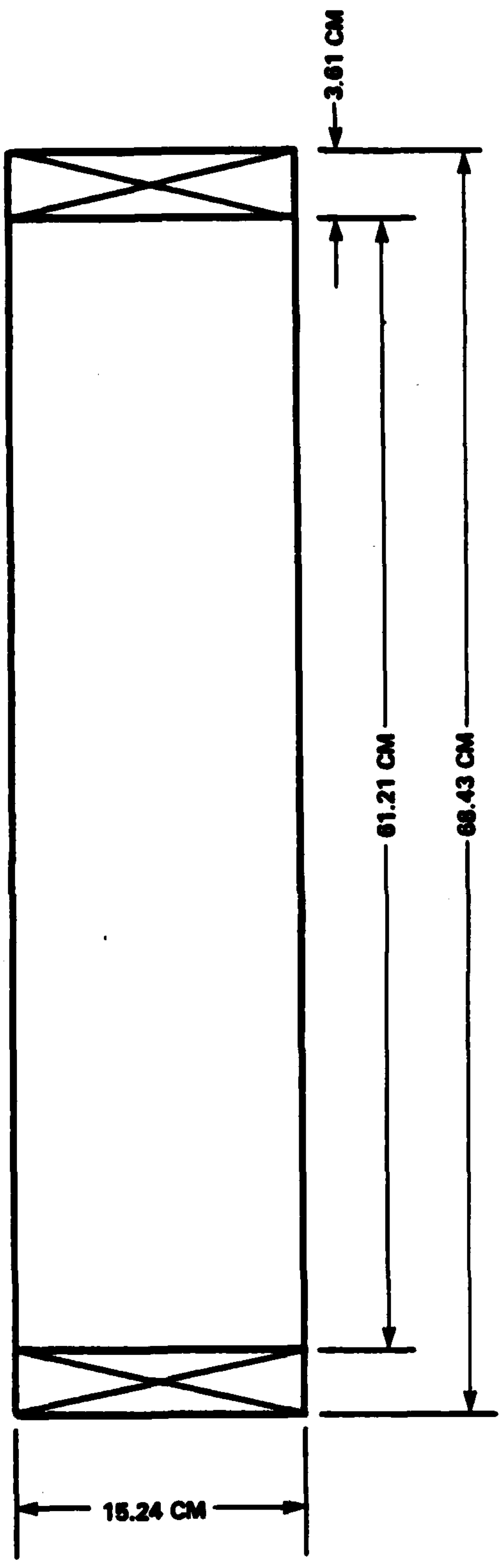


Figure 1 - Cross-Sectional View of the 0.61-Meter Test Coil

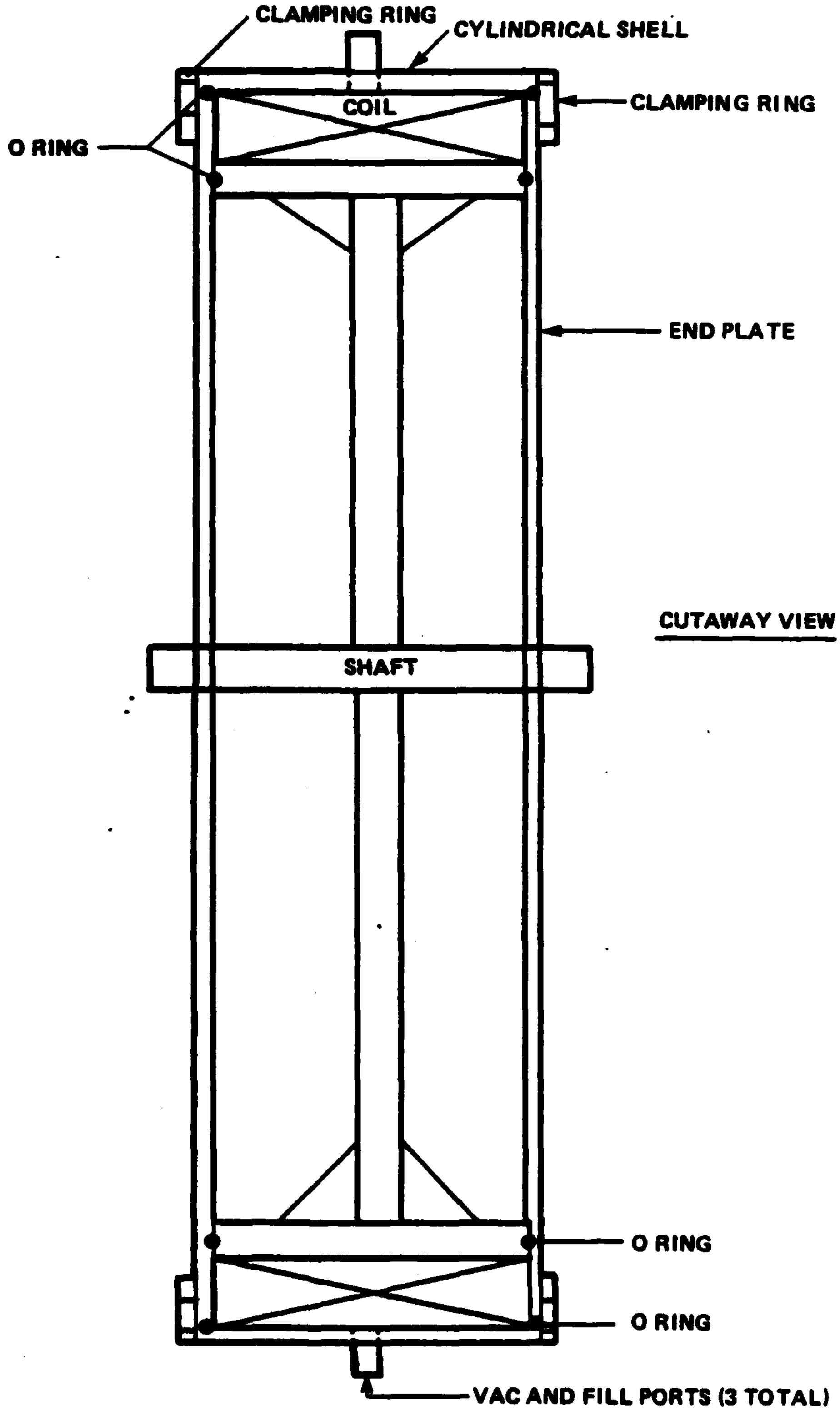


Figure 2 - 0.61-Meter Magnet Winding Coil Form and Potting Chamber

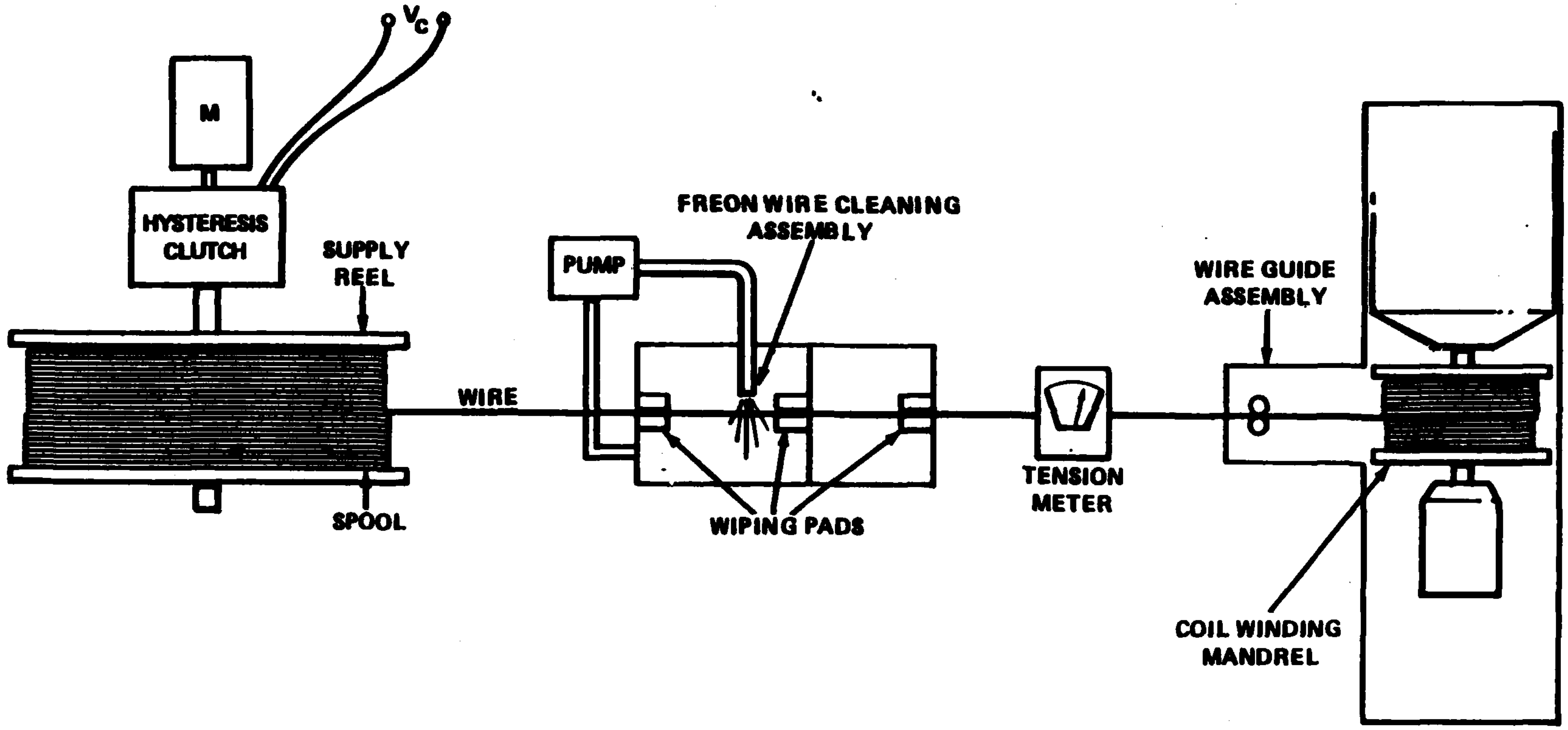


Figure 3 - Superconducting Coil Winding System

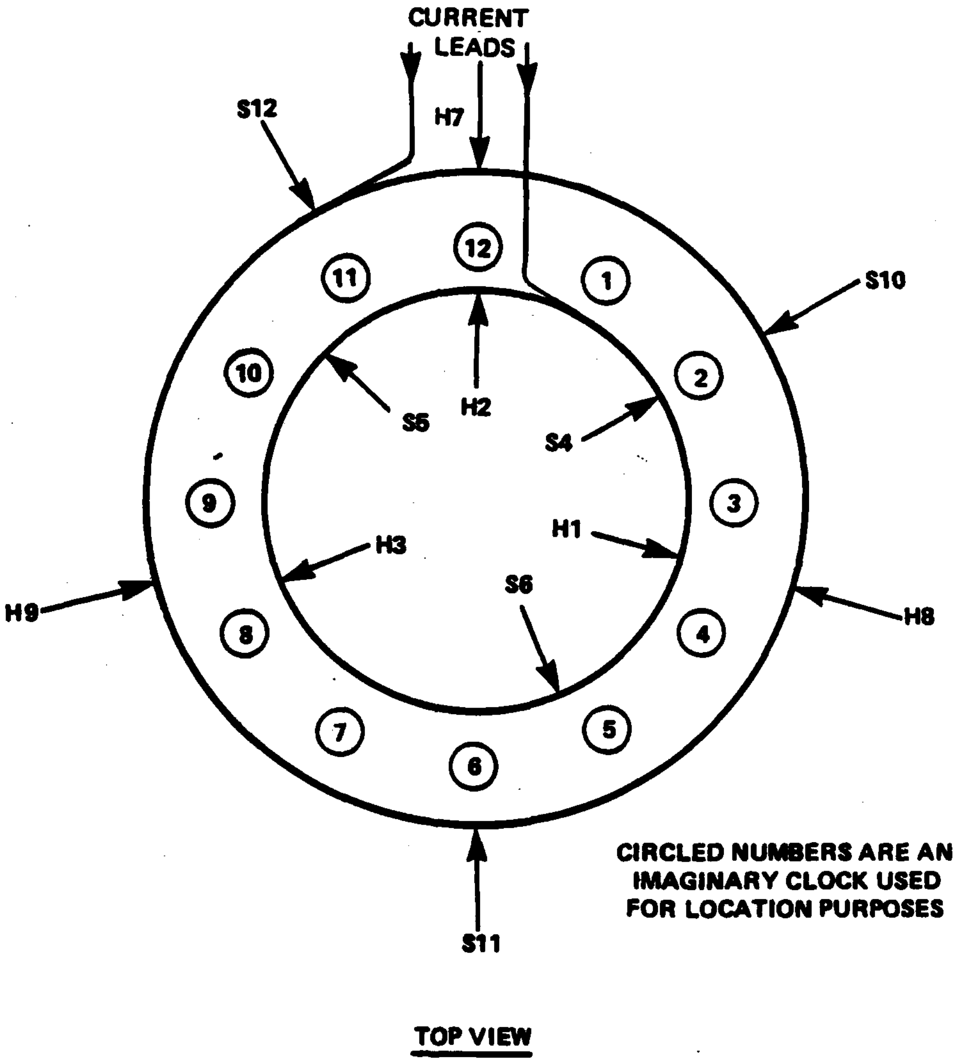


Figure 4 - 0.61-Meter Test Coil Instrumentation Location Diagram

Figure 5 - Test Coil/Potting Chamber Assembly

Figure 6 - Test Coil/Potting Chamber Assembly Installed
in a Thermally Insulated Box

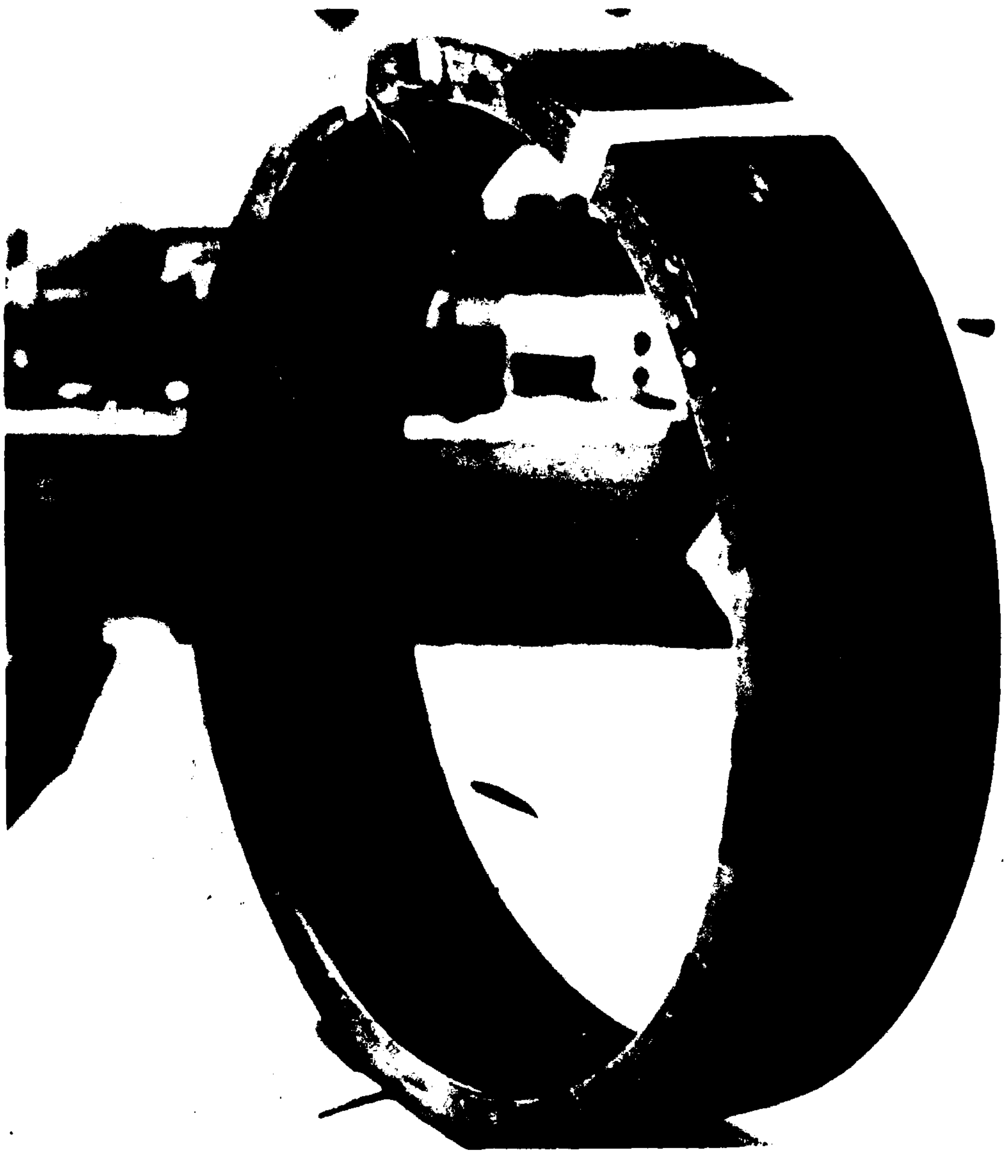


Figure 7 - 0.61-Meter Test Coil After Removal of Excess Epoxy

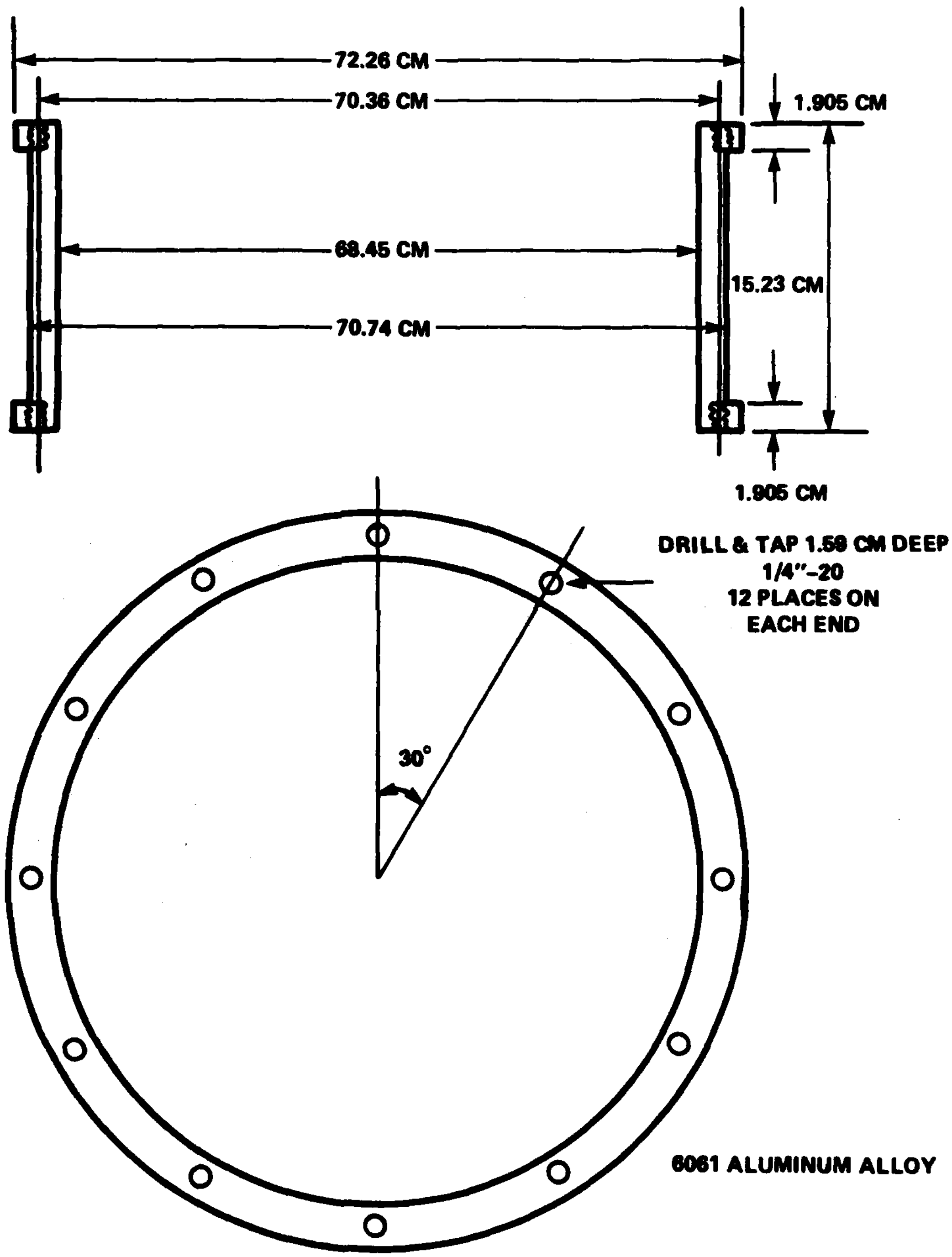


Figure 8 - Test Coil Cylindrical Retaining Ring

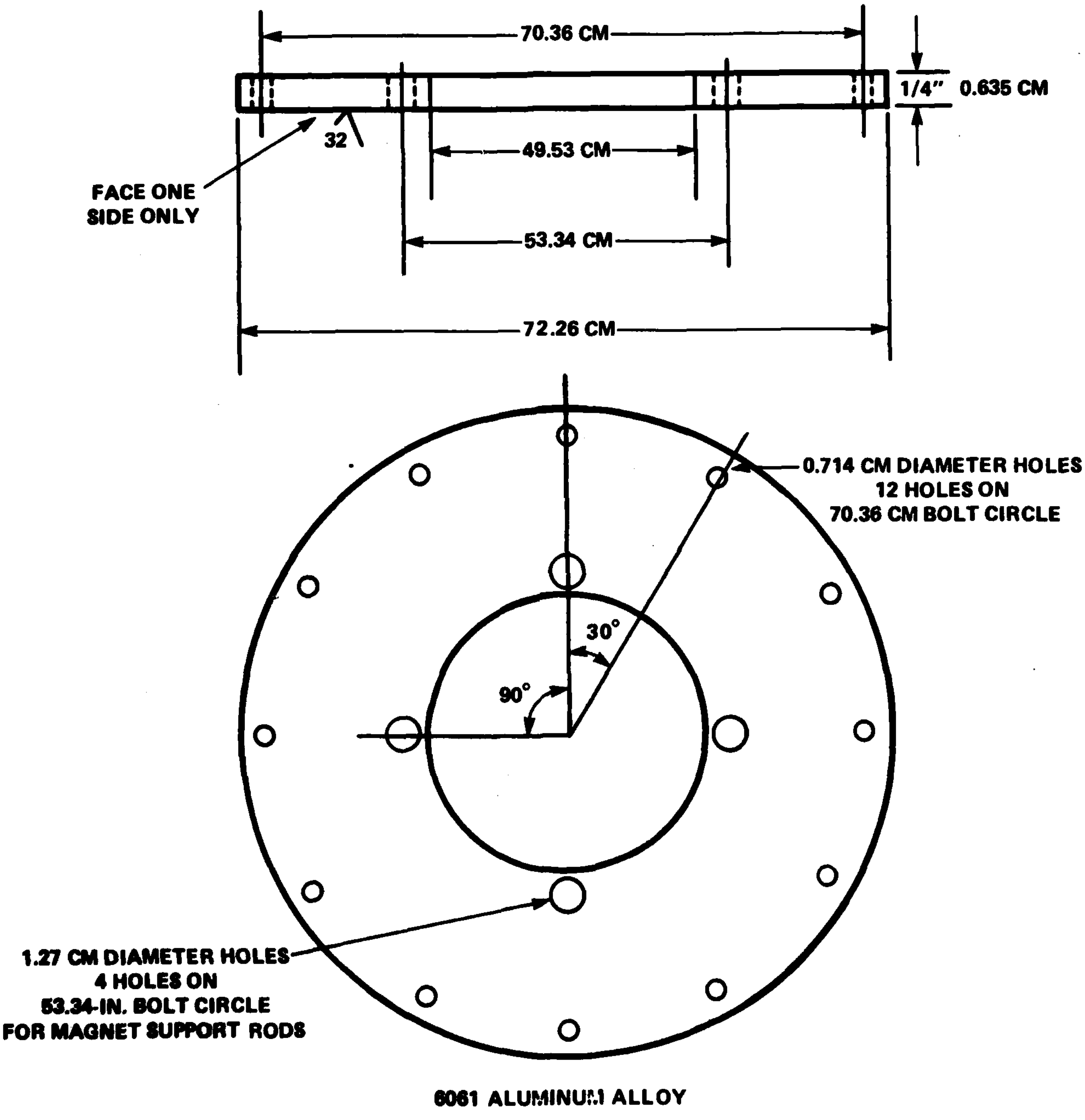


Figure 9 - Lower Coil Support Disk

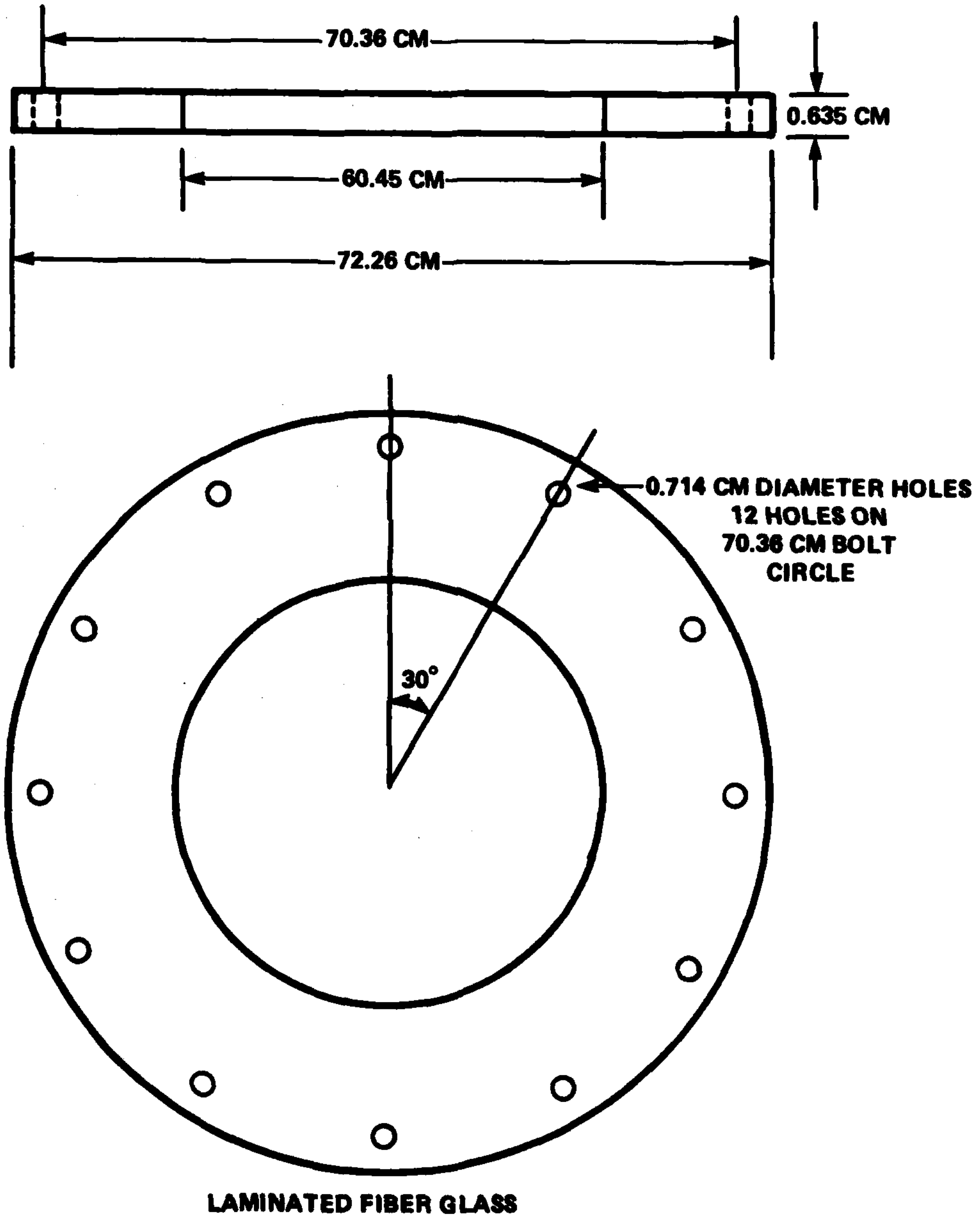


Figure 10 - Upper Coil Disk

Figure 11 - Completed Test Coil

Figure 12 - Completed Test Coil and Support System

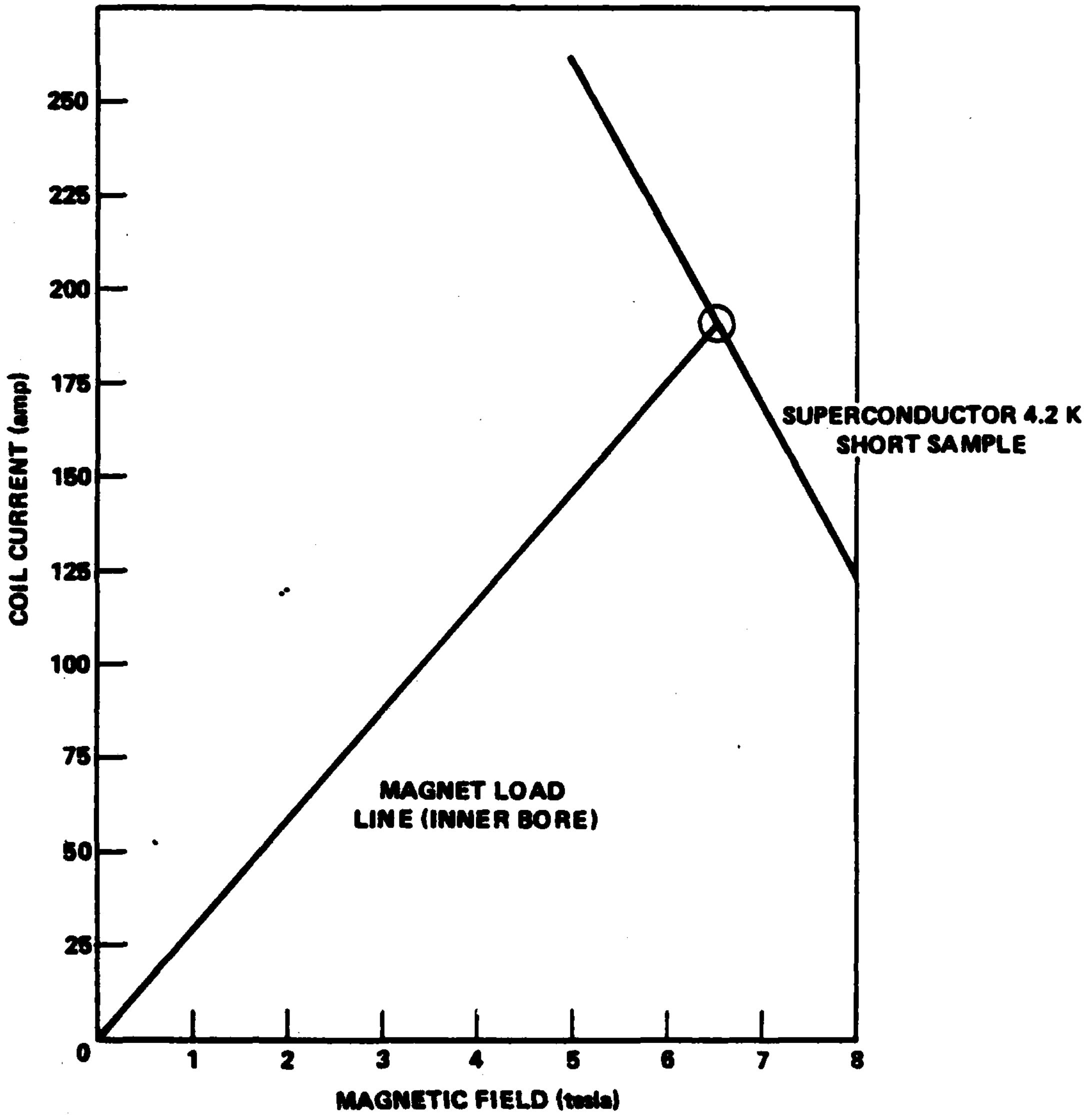


Figure 13 - Magnet Load Line and Conductor Short Sample

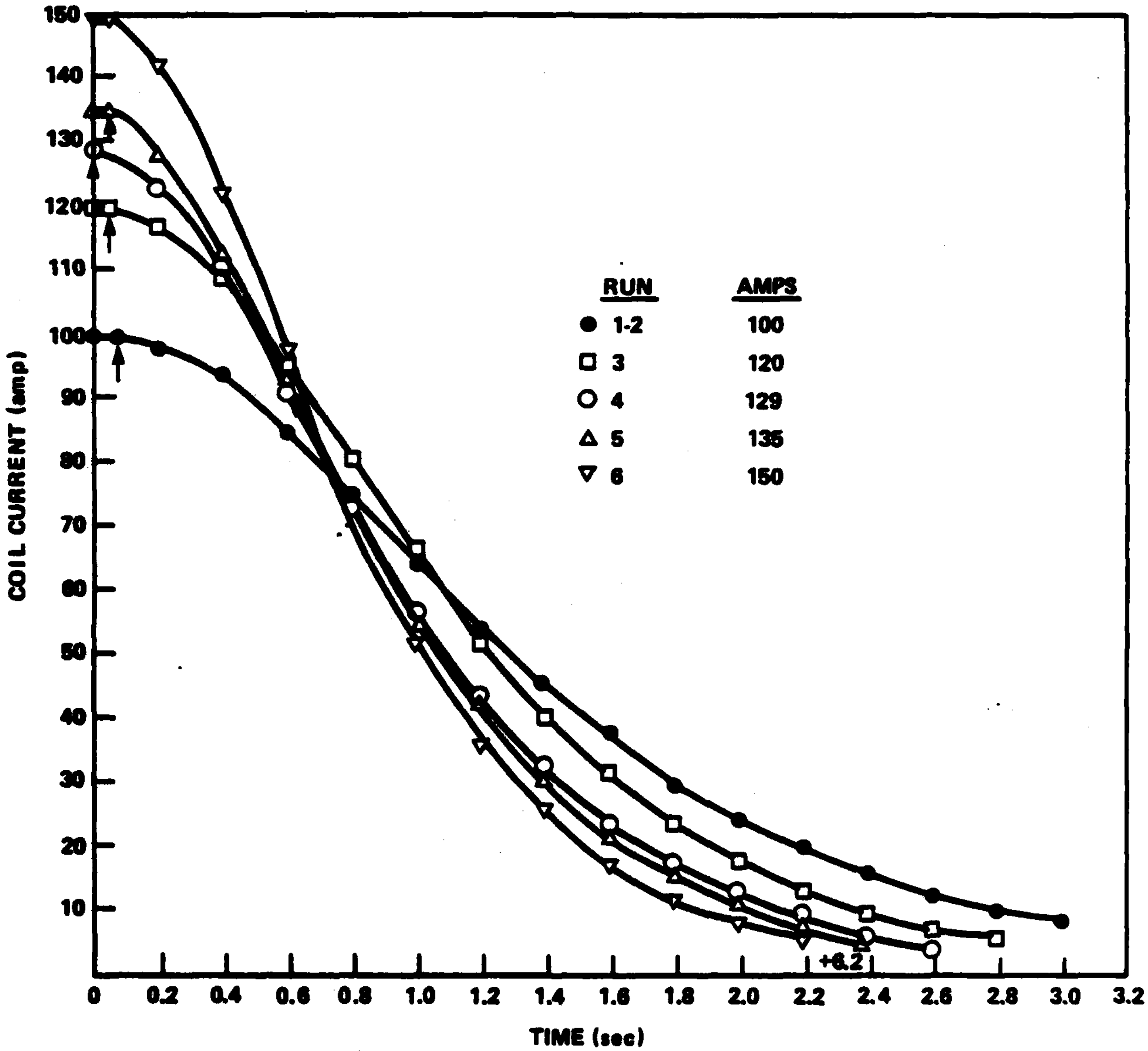


Figure 14 - Measured Coil Current for Quenches Initiated at Various Operating Currents

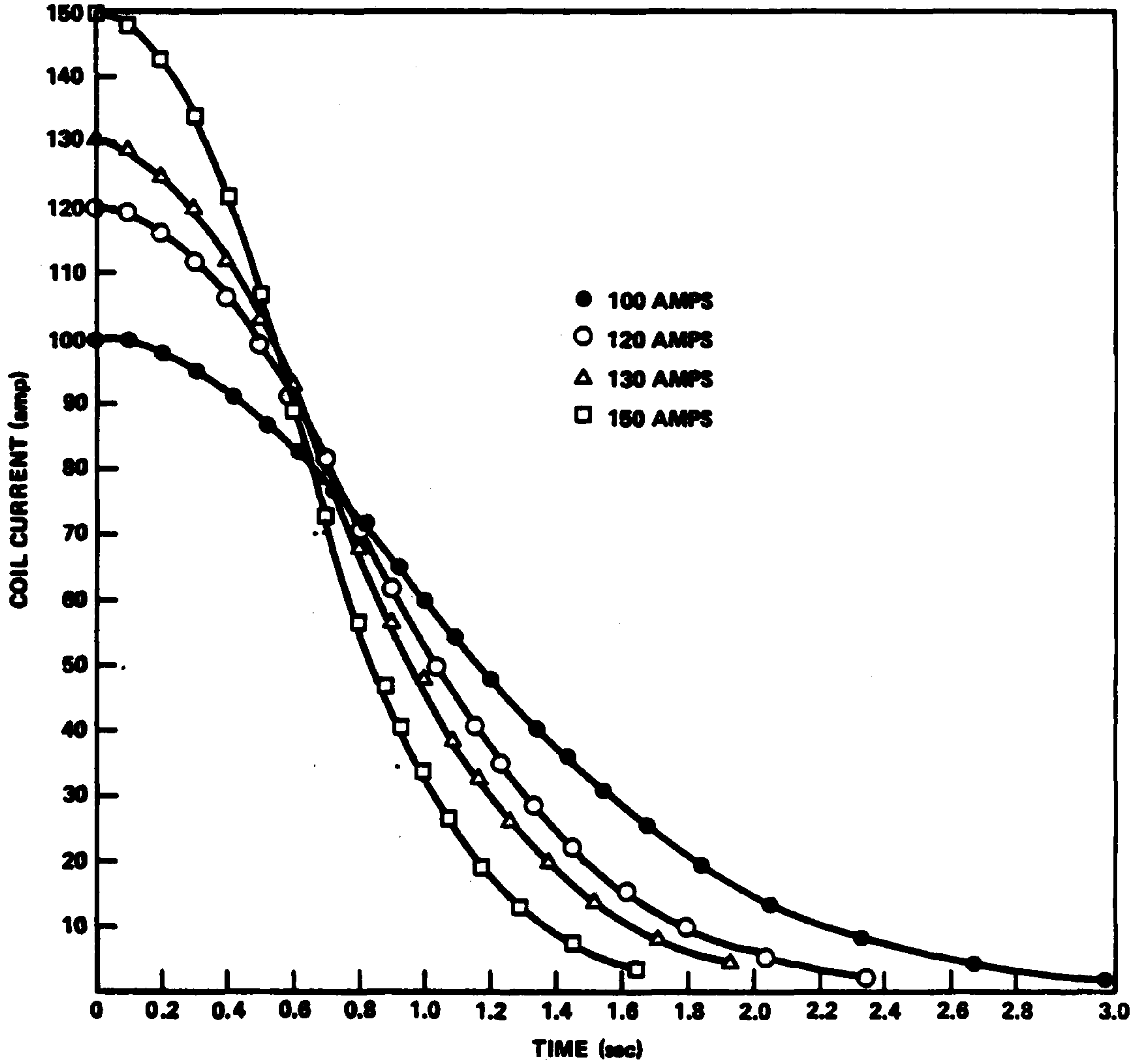


Figure 15 - QUENCH Computer Simulation Coil Current Results

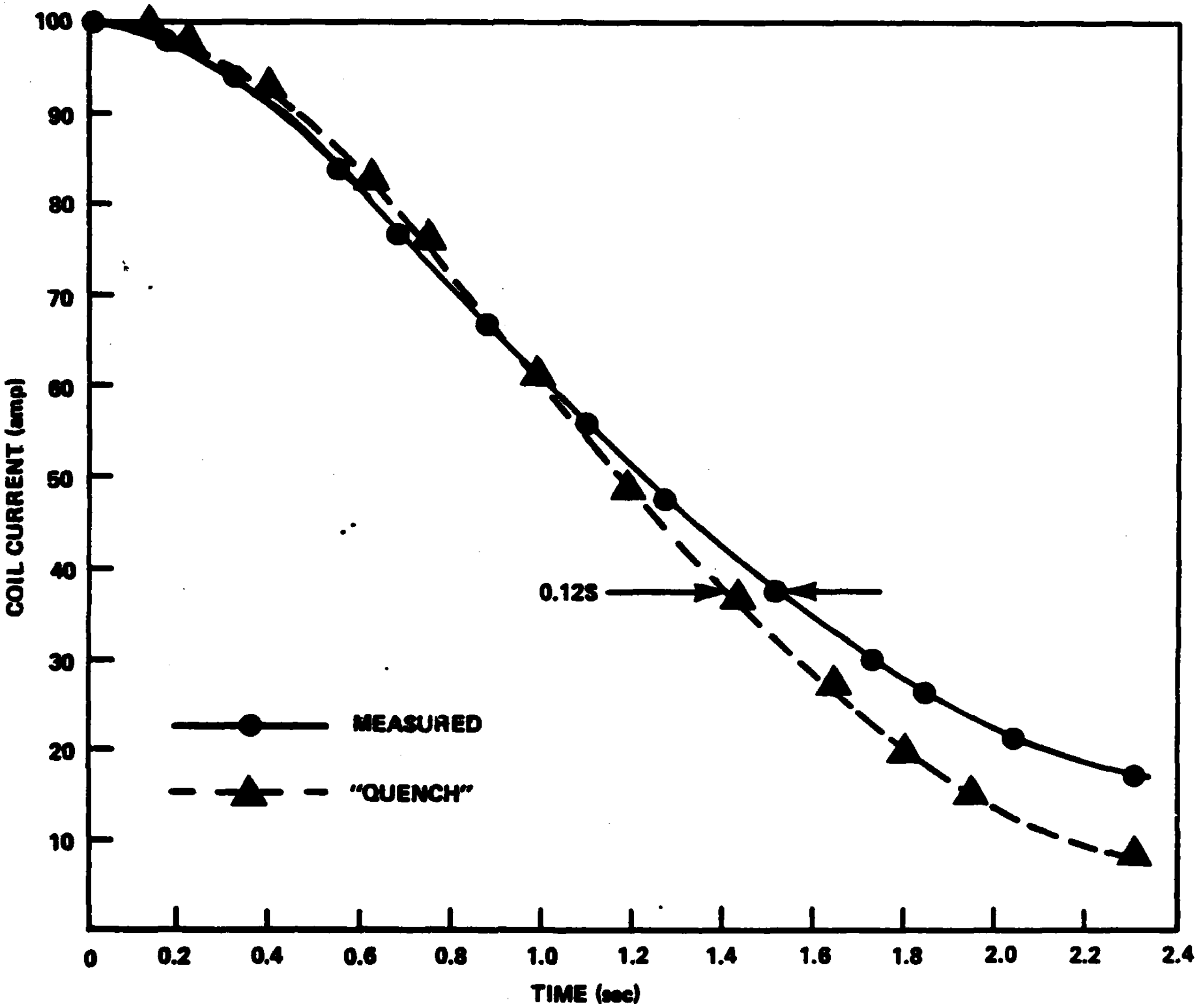


Figure 16 - Comparison of Measured and QUENCH Computer Program Results at 100 Amperes

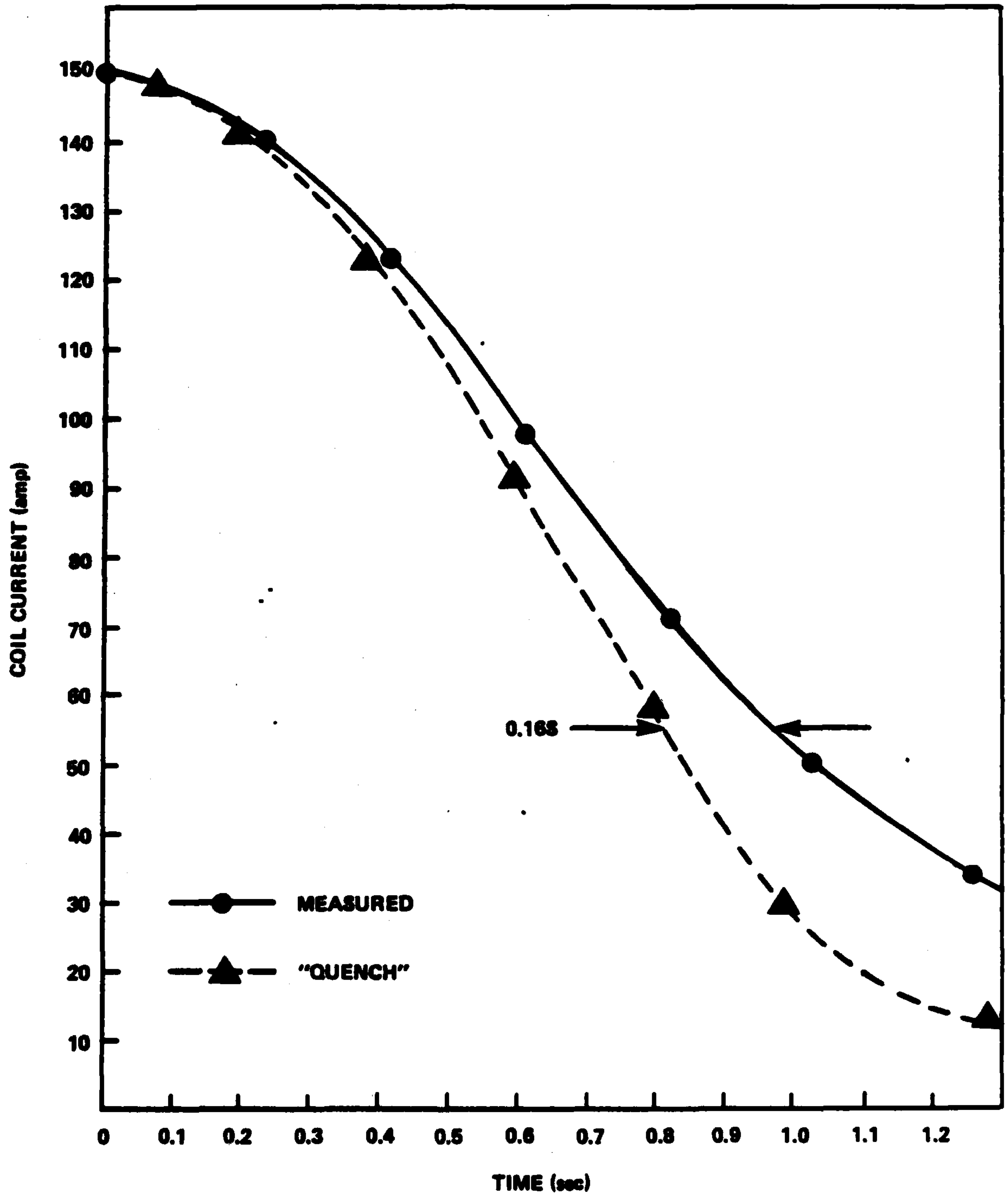


Figure 17 - Comparison of Measured and QUENCH Computer Program Results at 150 Amperes

INITIAL DISTRIBUTION

Copies

5 NAVSEA
1 SEA 05D
1 SEA 05R31
1 SEA 56Z31
2 SEA 99612

2 ONR
1 Code 410
1 Code 414

12 DTIC

2 Westinghouse Electric Company
R&D Center
1310 Buelah Road
Pittsburgh, PA 15235
Attn: J. Parker
R. Fernachak

1 General Electric Company
Corporate R&D
P.O. Box 43
Schenectady, NY 12301
Attn: R. A. Marshall

1 AiResearch Manufacturing Company
2525 West 190th Street
Torrance, CA 90509
Attn: W. Rumer

CENTER DISTRIBUTION

Copies	Code
2	271
20	2712
1	522.1
2	5231

DTNSRDC ISSUES THREE TYPES OF REPORTS

1. DTNSRDC REPORTS, A FORMAL SERIES, CONTAIN INFORMATION OF PERMANENT TECHNICAL VALUE. THEY CARRY A CONSECUTIVE NUMERICAL IDENTIFICATION REGARDLESS OF THEIR CLASSIFICATION OR THE ORIGINATING DEPARTMENT.

2. DEPARTMENTAL REPORTS, A SEMIFORMAL SERIES, CONTAIN INFORMATION OF A PRELIMINARY, TEMPORARY, OR PROPRIETARY NATURE OR OF LIMITED INTEREST OR SIGNIFICANCE. THEY CARRY A DEPARTMENTAL ALPHANUMERICAL IDENTIFICATION.

3. TECHNICAL MEMORANDA, AN INFORMAL SERIES, CONTAIN TECHNICAL DOCUMENTATION OF LIMITED USE AND INTEREST. THEY ARE PRIMARILY WORKING PAPERS INTENDED FOR INTERNAL USE. THEY CARRY AN IDENTIFYING NUMBER WHICH INDICATES THEIR TYPE AND THE NUMERICAL CODE OF THE ORIGINATING DEPARTMENT. ANY DISTRIBUTION OUTSIDE DTNSRDC MUST BE APPROVED BY THE HEAD OF THE ORIGINATING DEPARTMENT ON A CASE-BY-CASE BASIS.

END

FILMED

1-84

DTIC